DEFECT CONDEMNATION
FOR
SUBMARINE PRESSURE HULL WELDS

J.R. Matthews — J.F. Porter — T. MacAdam

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Head / Dockyard Laboratory (Atlantic)

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ABSTRACT

The British standards for submarine pressure hulls indicates that the presence of any lack of fusion defects in the weld is cause for rejection. However, depending upon the size and location of the defect, certain amounts of lack of fusion may be acceptable.

Six explosion bulge test panels were welded to have lack of fusion flaws; two panels had root flaws and the other four had cap flaws. Explosion bulge tests were performed to determine if the welds could resist crack propagation beyond the limits of the bulge apex.

Prior to testing, the welds were examined with manual ultrasonics and computer-aided ultrasonics. They were also radiographed at plus and minus 20 degrees to normal (standard radiography would be shot at normal). The NDT was conducted to relate performance back to NDT (as opposed to just defect size and location).

Following explosion testing, the welds were sectioned and opened to determine the true defect extent.

Defect size and location was found to be less of a determining factor in the quality of the weld than the base properties of the weld and steel. It was found that condemnation criteria should be based on these base properties as well as on the size and location of defects.

RÉSUMÉ

Les normes britanniques des coques pressurisées des sous-marins indiquent que la présence de défauts de manque de fusion dans la soudure est une cause de rejet. Toutefois, selon la grosseur et l'emplacement du défaut un certain manque de fusion peut être acceptable.

Six panneaux d'essai de bombement par explosion ont été soudés pour produire des défauts de manque de fusion; deux d'entre eux avaient des défauts de racine et les quatre autres des défauts de sommet. Les essais de bombement par explosion ont été préformés pour déterminer si les soudures pouvaient résister à la propagation des fissures au-delà du sommet du bombement.

Avant l'essai, les soudures ont été examinées aux ultrasons, manuellement et avec l'assistance de l'ordinateur. Elles ont également été radiographiées à plus et moins 20 degrés par rapport à la normale (la radiographie standard ne s'effectue pas dans une direction normale). L'essai non destructif a été effectué pour relier le rendement à l'essai non destructif (et non simplement pour connaître la grosseur du défaut et son emplacement).

À la suite de l'essai par explosion, les soudures ont été sectionnées et ouvertes pour déterminer l'ampleur réelle des défauts.

On a constaté que la grosseur et l'emplacement des défauts étaient moins déterminants pour la qualité de la soudure que les propriétés de base de la soudure et de l'acier. On a trouvé que le critère de rejet devrait être basé sur ces propriétés de base autant que sur la grosseur et l'emplacement des défauts.

DREA Technical Memorandum 98/202

Defect Condemnation for Submarine Pressure Hull Welds
by
J.R. Matthews, J.F. Porter and T. MacAdam

EXECUTIVE SUMMARY

Background

This report summarizes 10 years of measured effort to revisit the question of weld acceptance for ships and submarines. Existing standards were adapted from standards that were adapted from other standards going back to a group of welding engineers in the late 1940's assessing the amount of rework that would be acceptable as opposed to the significance of the defects.

There are two ramifications of this work. First, existing standards are overconservative leading to excessive costs in fabrication and repair. New standards could therefore save millions of dollars. Second, the existing standards evolved for welding which typically exhibited structural transition in the $0^{\circ}C$ range. Newer pulsed gas metal arc welding developments easily produce structural transition in the -30 to $-40^{\circ}C$ range but have a propensity for lack of fusion defects which are not permitted in the current standards. While defects in material with a structural transition near $0^{\circ}C$ are quite serious those in materials of lower structural transition prove to be relatively unimportant.

In this work, welded panels with lack of fusion defects were created. Unlike typical studies of weld defects in which weld procedures were degraded to produce defects in weldments with poor base properties, this work was careful to produce weldments with good base properties with defects in them. The point here is that testing a defected weldment with poor properties can only give unacceptable results while testing an otherwise properly prepared weld with defects identifies the true consequence of the defects. Weldment base properties must be addressed separately from defect assessment (the latter is the subject of heat input control, weld monitoring, weld procedure development and testing).

Results

In this study six panels were prepared with root and cap lack of fusion defects. They were characterized by manual ultrasonics, computer-aided ultrasonics and radiography at plus and minus 20 degrees to normal (standard radiography would be shot at normal). The NDT was conducted to relate performance back to NDT (as opposed to just defect size and location). The panels were then subjected to the explosion bulge test to determine if the welds could resist crack propagation beyond the limits of the bulge apex. The defected welds performed acceptably (a tribute to the weldment quality preserved in the process of producing the defects). Following explosion testing, the welds were sectioned and opened to determine the true defect extent.

In summary, defect size and location was found to be less of a determining factor in the quality of the weld than the base properties of the weld and steel. It was found that condemnation criteria should be based on these base properties as well as on the size and location of defects.

Significance of Results

This work will have significant cost saving ramifications for the Navy and the welding steel industry (the latter a component in over 50% of the GDP of the world).

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1.0 INTRODUCTION

The British Naval standard for acceptance of welds in ships and submarines[1] indicates that the presence of any lack of fusion (LOF) defects in the weld is cause for rejection. In this report it is suggested that depending on the size and location of these defects, that certain amounts of lack of fusion may be tolerable. This report further suggests that rather than being concerned with crack initiation in the weld, it may be better to examine the resistance of that weldment to crack propagation.

Six explosion bulge test panels (TM1 through TM6) were welded to have lack of fusion flaws; two panels had root flaws (TM1 and TM4) and the other four had cap flaws. These flaws were non-destructively examined using radiographic and ultrasonic methods (manual and computer-aided) before the explosion bulge testing.

The explosion bulge tests were performed to determine if the welds could resist crack propagation beyond the limits of the bulge apex. The plates were explosively loaded to cause a strain of 16%. If, upon reaching this strain percentage, the crack in the weld had not extended beyond the bulge apex, the amount of lack of fusion defects would be considered tolerable. Using these results a comparison was made based on initial defect size and location (i.e. root or cap) and the ultrasonic reflectivity level.

2.0 D.G. SHIPS/G/10000B (NES 773)

There are three standards of acceptance for welds outlined in D.G. Ships/G/10000B. Class 1 "requires 100% examination for internal and surface flaws by the applicable NDT techniques (radiography, ultrasonic etc) together with visual examination"[1]. Typical applications include submarine structural and pipe system welds subjected to diving pressure and welds in Level 1 pipe systems as well as repairs to welds subject to these conditions. Class 2 welds also require 100% or selective examination for internal and/or surface flaws, by the applicable NDT techniques together with visual examination. Typical applications include submarine structural welds not subject to diving pressure and specific ship hull structural welds such as outer bottom butt welds, main watertight bulkheads, citadel boundaries, etc. Class 3 welds only require visual

examination. Typical applications include surface ship minor bulkheads, stools and brackets for minor fittings and Level 4 pipe systems.[1]

Using radiographic examination for class 1 welds, "welds shall be free from lack of fusion and incomplete penetration indications."[1] For class 2 welds there exists a lack of fusion chart which must be consulted (Figure 6, D.G. Ships/G/10000B).

Using ultrasonic examination, defect indications having a reflectivity of 12 dBs or more in excess of the reference standard in D.G. Ships/PS/9022, shall be cause for immediate rejection.[1]

This report is concerned only with class 1 welds. Other defect criteria for this class of weld include a minimum loss of area of less than 1% for all thicknesses of material due to uniformly distributed porosity. For aligned porosity not associated with lack of fusion non-metallic inclusions, welds may not have defects in excess of the limits shown in Figure 5 of D.G. Ships/G/10000B.

3.0 WELDED PLATES

Each panel consisted of two HY 100 steel plates welded together. Each plate was 25 mm thick and contained a double V-groove weld with 60 degree included angles and a root face of 0 mm. The weld groove was oriented perpendicular to the rolling direction.[2]

The welds were made to have controlled lack of fusion flaws; two panels had root flaws and the other four had cap flaws. A root flaw is an interpass or side wall lack of fusion in the root region, and a cap flaw is similarly an interpass or side wall lack of fusion in the cap passes.

3.1 Welding

Electric resistance heating was used to preheat the welds. A Honeywell electronic chart recorder coupled with a 6 zone mini-controller and a 75 kW transformer were connected to the two heaters and two K-Type thermocouples were spot welded to the panels to control and record the temperature. Interpass and preheat temperatures were monitored and welding was delayed until interpass temperatures were reduced to

acceptable values. After welding was complete, the panels were wrapped in insulation and allowed to cool to room temperature at which point NDE was conducted.[2]

Welding procedures were prepared and the influence of parameter changes was investigated using the ER120S-1 weld wire. The parameters giving the most desirable effects were then used to create the defects.[2]

Backgrinding to sound metal of the root prior to welding Side 2 was conducted on all panels. Electrical grounding of the workpiece was accomplished by clamping the ground cable in the line of the weld groove. In all cases the welding progression was towards the ground.

In depth details of the welding procedure used may be obtained in Appendix A of reference 2.

3.2 Lack of Fusion Defects

Lack of fusion, or incomplete fusion denotes a planar weld discontinuity caused by incomplete coalescence of the filler metal with the base metal. Incomplete fusion may be found in any layer or pass of a welded joint and almost always occurs as a result of improper welding techniques for a given joint geometry. Most Gas Metal Arc Welding (GMAW) processes are especially prone to this form of discontinuity and their presence is greatly influenced by the composition of the shielding gas. The T.I.M.E.™ Process, a revolutionary modification of GMAW, has been engineered to reduce incomplete fusion. The T.I.M.E.™ shielding gas generates intense heat in the arc and is considered to be much more reliable in eliminating fusion defects than other gas mixes. However, in joining high strength materials such as HY 100, the application of low heat inputs needed to achieve high notch toughness can give rise to the incidence of incomplete fusion.

The middle third of the plate is the region where lack of fusion defects are most likely to be implanted without the operator's knowledge.

Incomplete fusion may be caused by:

1. incorrect electrode position
2. weld metal running ahead of the arc

3. dirty steel
4. filler metal characteristics
5. welding procedure (e.g. insufficient current, too long an arc, improper joint design, insufficient heat input)

Root lack of fusion defects are very sensitive to increases in arc voltage (PV) due to the constriction of the joint. The root defects in plates TM-1 and TM-4 were created by increasing PV from -3.5 to +3.0, an increase in arc voltage of approximately 6 volts.

Cap defects are difficult to produce and are unlikely to occur in fabrication with responsible operators. The conditions required for such defects to occur would be noticed during normal welding operations. Lack of fusion defects are most likely to be implanted within the middle third thickness region of the plate without operator knowledge.

Root defects were introduced only on Side 2. Cap defects were implanted on the final layers of both Side 1 and Side 2. UT was used to determine the most suitable side for further evaluation and was subsequently ground smooth for explosion bulge testing.

4.0 NON-DESTRUCTIVE TESTING

Before the explosion bulge testing, the flaws were non-destructively examined at DREA using manual ultrasonic inspection, computer-aided ultrasonic inspection (using APHIUS, the Automated Pressure Hull Intelligent Ultrasonic System[3]) and radiographic methods.

4.1 Manual Ultrasonics

Ultrasonic inspection was employed to characterize and measure the depth of discontinuities. The UT was performed using a Sonic MK I and an A85087 transducer with a probe angle of 70°. This probe angle has been found to be most effective in finding the lack of fusion defects in this joint configuration. The reference reflections were calibrated in accordance with ASME VIII and based upon a 3/32" diameter hole in the calibration block. TJ Inspection Services were contracted to perform the manual UT inspections.

For these butt joint welds, the acceptance criteria was dependent on signal level. For a reflectivity of 12 dB or more in excess of the reference standard in DG Ships/PS/9022 rejection was automatic. For reflectivity greater than the reference but less than 12 dB greater than the reference, acceptance was determined when:

a) the maximum length of a continuous defect is less than t or 38 mm, whichever is less (t = 25 mm)

b) defects are separated by at least 1.25l of acceptable weld metal (l = length of the larger defect); clusters of small defects shall be assessed as a single indication

c) the total length of defect in any 1200 mm length of continuous weld shall not exceed 75 mm (proportional for weld lengths less than 1200 mm)[1]

Defect indications having a reflectivity equal to or less than the reference standard in D.G. Ships/PS/9022 may be accepted, provided that all the following conditions are met:

a) as (b) above

b) the maximum length of a continuous defect is less than 2t or 75 mm, whichever is less (t = 25 mm)

c) the total length of defect in any 1200 mm length of continuous weld shall not exceed 150 mm (proportional for weld lengths less than 1200 mm)[1]

Table 4.1.1: Manual ultrasonic test results for the 6 plates.

Plate	Flaw Type	Reflectivity	Length (mm)	Observations
TM-1	root	+100 %	50	side 2 ground
TM-2	cap	50-100 %	50	side 2 ground for testing
TM-3	cap	+100 %	50	side 2 ground for testing
TM-4	root	+100 %	100	side 1 ground
TM-5	cap	50-100 %	100	side 1 ground for testing
TM-6	cap	+100 %	100	side 1 ground for testing

The initial internal flaw lengths were marked on the convex surface.

4.2 Computer-Aided Ultrasonics (APHIUS)

The system used for computer-aided ultrasonic evaluation was APHIUS, the Automated Pressure Hull Intelligent Ultrasonic System.[3] APHIUS offers increased safety and reliability as well as lower refit costs. It contains a high-performance ultrasonic pulser with receiver and state of the art digitization for rapid data acquisition and processing. The ultrasonic pulser features both square waves and tone burst operation in one complete digitally controlled package. It can operate in Pulse/Echo mode through the same transducer or Pitch/Catch mode with dual transducers. The receiver operates in broadband and tuned modes.

APHIUS provides high-speed, high capacity data acquisition. It has a high inspection productivity and reliability due to a combination of functionality and performance. It provides computer assistance to an inspector in four ways:

1. permanently recording the defect indications
2. mapping the location of the flaws
3. displaying standard ultrasonic information during the test
4. sorting the indications as to type of flaw, with particular reference to cracks, slag and porosity.

APHIUS produces longitudinal B-scans which show the depth of defects. Transverse B-scans indicate the location of defects in the weld profile. APHIUS is referred to as intelligent because it can help the operator distinguish between tolerable defects and those calling for material condemnation.

The characteristics of the initial defects as determined using the APHIUS system are shown in Table 4.2.1 below.

Table 4.2.1: Computer-Aided Ultrasonic test results for the 6 plates.

Plate	Reflectivity	Length (mm)	Depth (mm)	Observations
TM-1	120 %	38	11	
TM-2 side 1	30-60 %	51	3.5	
TM-2 side 2	50-100 %	51	3.5	
TM-3 side 1	100-120 %	64	3.5	
TM-3 side 2	100-120 %	64	3.5	
TM-4	140 %	114	10	
TM-5 side 1	50-100 %	102	3.2	intermittent cracks
TM-5 side 2	50-100 %	127	3.2	
TM-6 side 1	50-110 %	127	2 and 3.5	
TM-6 side 2	50-100 %	127	3.5	

Defect length and reflectivity results are similar to those provided by the manual ultrasonic inspection whose results may be seen in Table 4.1.1. APHIUS, however, also indicates the depth of the flaw.

A top view printout of the APHIUS results from each of the six plates is found in Annex A.

4.3 Radiography

Radiographic examination was carried out using methods described in DG Ships/PS 9022. To ensure greater detection results, x-rays were taken at angles plus and minus 20° from normal incidence (the normal practice is to take a single shot at 0°).

Indications were considered separately if the ends of two adjacent indications were separated by a distance greater than the larger of the following:

    a) 2.25t (where t = thickness of the plate, 25 mm)

    b) 1.25l (where l = length of larger indication)

The acceptable length must be reduced proportionally for welds less than 150 mm.

On a radiograph a lack of fusion defect will appear as a black mark. The negatives of the x-rays which showed the most defects for each plate are shown in Figures 4.3.1 to 4.3.6. On these negatives, defects appear as white marks.
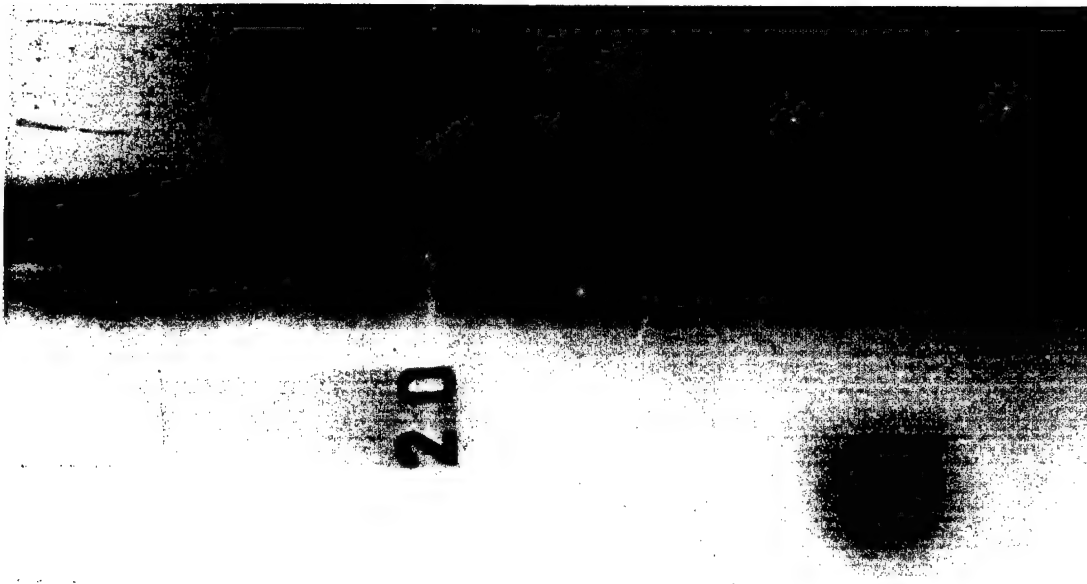
Figure 4.3.1: Radiograph of panel TM-1 taken at 20° to normal.
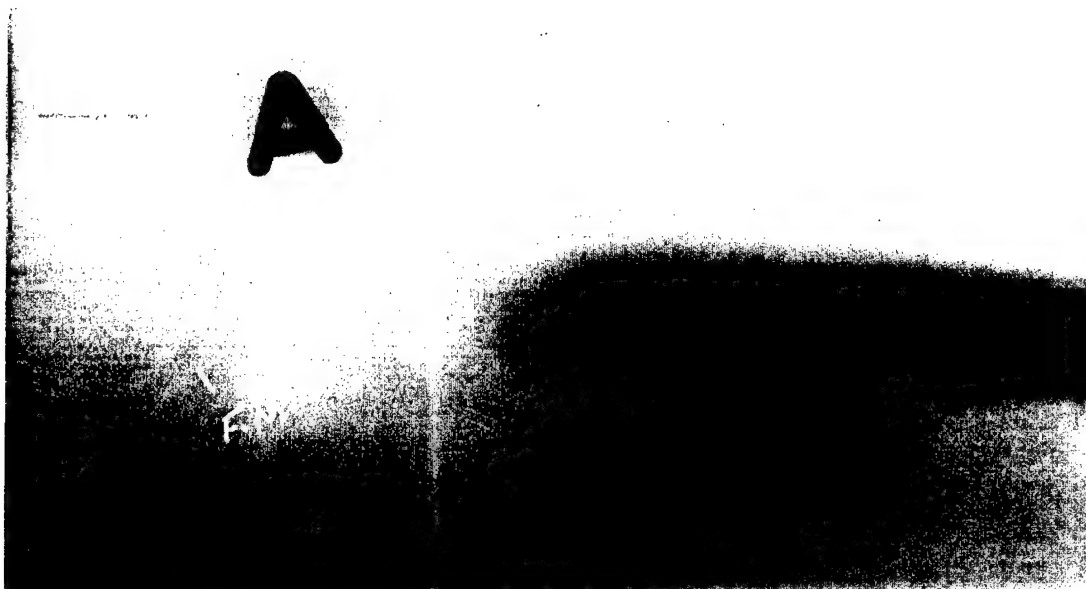

Figure 4.3.2: Radiograph of panel TM-2 taken at 20° to normal.
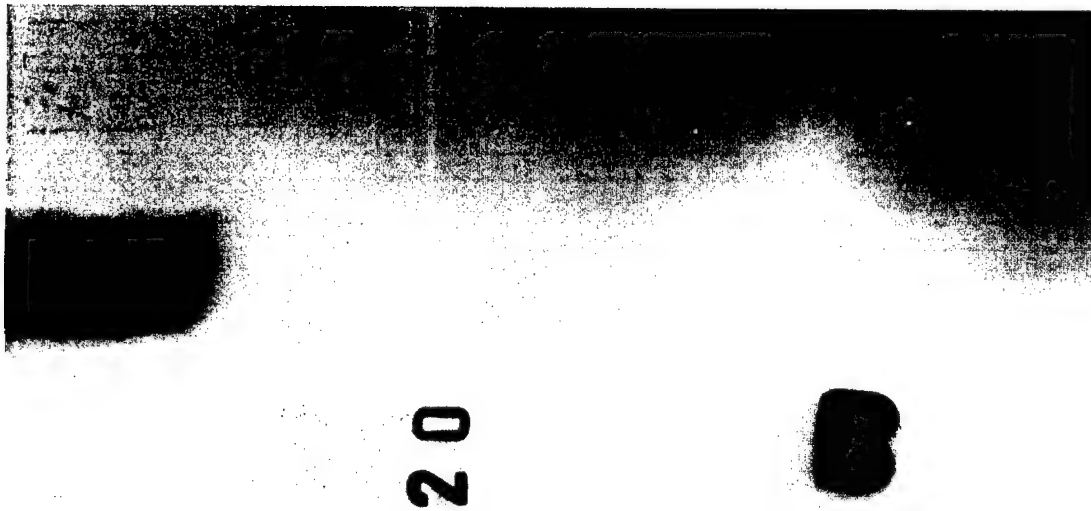
Figure 4.3.3: Radiograph of panel TM-3 taken at 20° to normal.

Figure 4.3.4: Radiograph of panel TM-4 taken at 20° to normal.

Figure 4.3.5: Radiograph of panel TM-5 taken at 20° to normal.

Figure 4.3.6: Radiograph of panel TM-6 taken at 20° to normal.

By taking two shots at plus and minus 20° to normal more of the lack of fusion defect could be seen than by taking a single shot normal to the plate. At +20 we detected very little of two defects and half of one of them. At –20 we detected half of one defect but the majority of the rest. Using both +20 and –20 we found all of four defects and 90% of the other two. Clearly this enhanced approach to radiography is technically as successful as computer-aided ultrasonics.

5.0 EXPLOSION BULGE TESTING

Controlled amounts of lack of fusion were introduced in pulsed GMAW weldments of HY100 and explosively deformed using the DREA underwater explosion bulge procedure.[4]

An important consideration in the certification of a candidate submarine pressure hull metal or weldment is the material's ability to attain high levels of dynamic plastic deformation, prior to the formation and propagation of a crack. In order to test the integrity of these metals and weldments under shock loading, the explosion bulge test was developed in 1949-1950.[5] It is a simple and reliable method for determining plastic strain performance characteristics of weldments. Explosion bulge tests are used extensively to investigate the factors which determine the performance of weldments, particularly in submarine and other large welded structures.[5]

The test involves explosively loading a flat test plate specimen or weldment on a circular test die. The test plate is then tested by repeated explosive shots until fracture occurs or until the minimum reduction in thickness required is met (reduction in thickness is directly proportional to surface plastic strain). This test allows the critical regions of the weldment to be assessed under high strain rate loading.[5]

5.1 Procedure

Test specimens must be cooled (refrigerated) to a temperature below the required test temperature so that any heat gain during handling will not cause the test temperature to be exceeded. Test specimens being cooled must also be allowed to normalize in

temperature through thickness (normally 1 hour per inch). A thermocouple is used to monitor the test plate temperature.

A square, 24 inch wide, full thickness sample is placed on an anvil which had a 15 inch diameter circular cut-out removed, with the ground hold down surfaces contacting the die. The explosive charge is suspended over the center of the specimen, maintaining the proper stand-off distance. When the test piece has attained the proper temperature, the charge is detonated creating a uniform gas pressure which clamps the test piece to the anvil. The pressure wave deforms the test plate material into the anvil opening, developing a balanced biaxial plastic set strain field in the bulge apex region of the test piece (for an unwelded sample). Charge weights and standoff distances should be selected to achieve an approximate 3% thickness reduction (measured near the center) for each shot. The stand-off distance is also set such that the explosive shock wave is planar and uniformly loads the entire plate surface. Table 5.1.1 indicates the recommended charge weights and stand-off distances for HY80 and HY100 steels for in air detonation.[5]

The clamping effect of the plate to the anvil is important to the efficient generation of the bulge apex strain levels. Loss of this clamping would delay the transition of the bending wave deformation action to the membrane stretching biaxial elongation. Sufficient stand-off distance is also required to eliminate the impulse loading effects generated by contact charges.

After each shot, the specimen is examined, and the location, length and direction of all cracks recorded. Before each successive explosive loading, the test specimen should be returned to the cooling medium long enough to thermally recondition them.

In the DREA underwater version of the test, prior to detonation, the entire test assembly is submerged in a water filled pit. The water acts as an efficient explosive energy transfer medium between the charge and test piece thus relieving the weight of explosives to affect the required deformation.

Table 5.1.1: Nominal charge size, nominal pentolite charge weight and stand-off distances recommended based on metal type and nominal thickness for testing in air.[5]

Metal Type	Nominal Thickness (in.)	Nominal Charge Size	Nominal Pentolite Charge Weight (lbs)	Stand-off Distance (in.)
HY-100	2	10 diam. x 7.3 ht.	30	15-16
HY-80	2	10 diam. x 6 ht.	24	15-16
HY-80	1	7 diam. x 3.5 ht.	7	15-16

5.2 Results

The explosion bulge tests caused the initial lack of fusion flaws to propagate. The root flaws propagated through the thickness of the plate whereas the cap flaws only extended by small amounts on the convex side, in all cases propagating to that surface. The cap flaws on the concave side did not propagate. The mechanism of flaw propagation was identified as ductile as observed.

Measurements were taken of both the initial and final flaw lengths and depths. Photographs displaying the appearance of the final flaws emerging on the convex surface of the test panel may be observed in Figures 5.2.1 - 5.2.6.

Table 5.2.1: Charge weights and stand-off distances used during underwater explosive bulge testing for plates TM1-6 and results of each loading.

Plate	Shot	Stand-off (in.)	Charge Weight (lbs)	Strain (%)	Length and Observations
TM-1	1	6	8	8.5	no tears
	2	6	8	17.3	through thickness fracture
TM-2	1		4	11.4	short tears, tensile side (~2 in.)
TM-3	1	6	4	10.3	2½ in. shallow tears (tensile side)
TM-4	1	6	6	7.4	no tears
	2		6	16.7	through thickness crack
TM-5	1	6	5.25	13.0	2 inch tear (tensile surface)
TM-6	1		8	14.4	

The cap flawed specimens were deformed less than the root flawed specimens because the initial charge broke the surface of the cap flawed specimens and these tests were ended. The root flawed specimens were deformed by a second shot until the defects broke the surface.
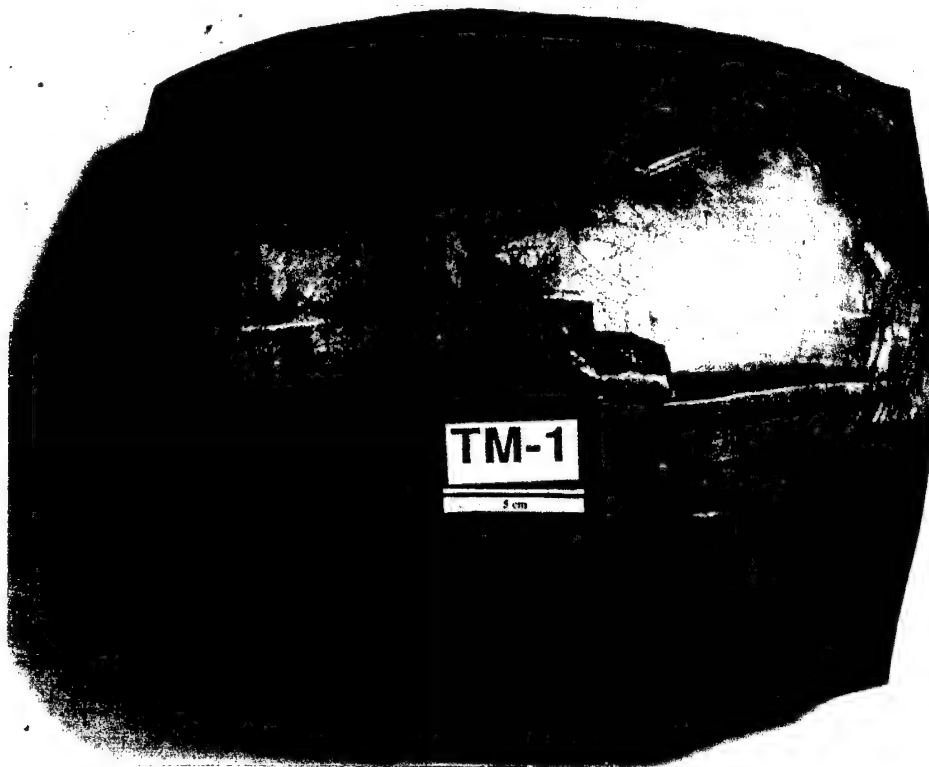
Figure 5.2.1: Panel TM-1 contained root flaws (yellow marks indicate the initial flaw length determined by UT)
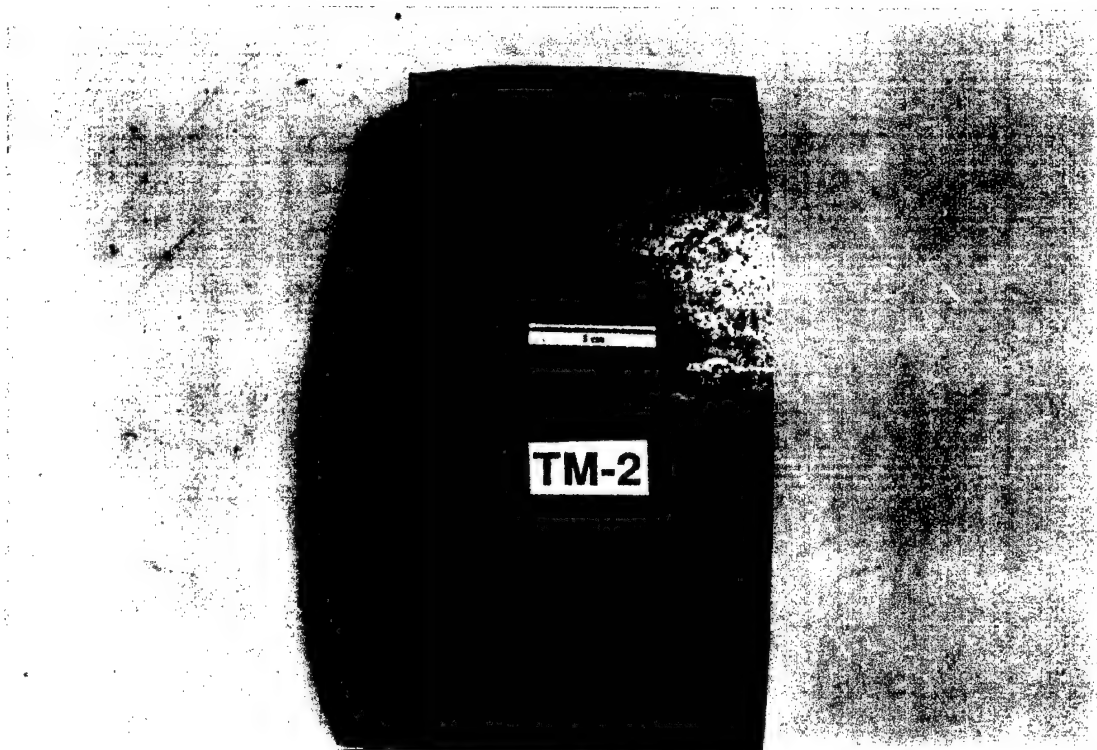

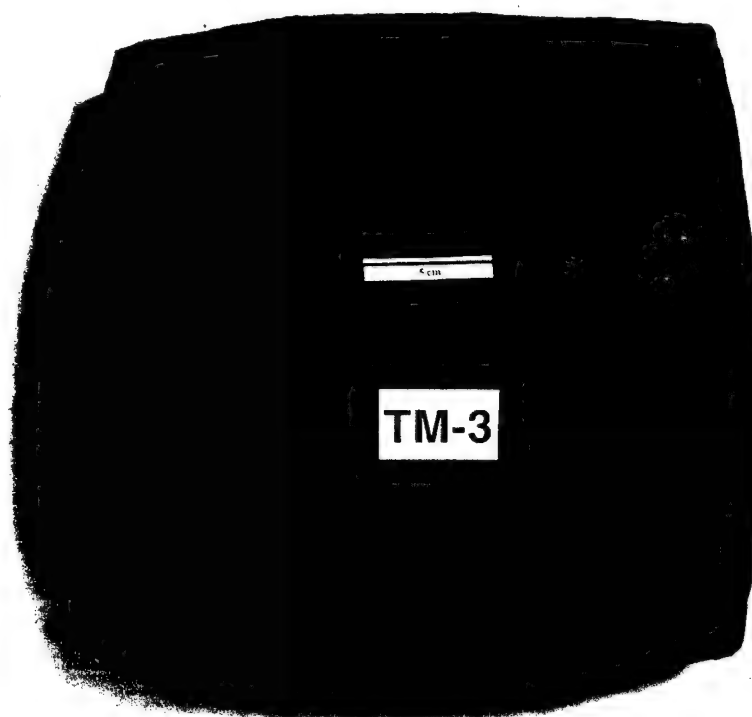
Figure 5.2.2: Panel TM-2 contained cap flaws.

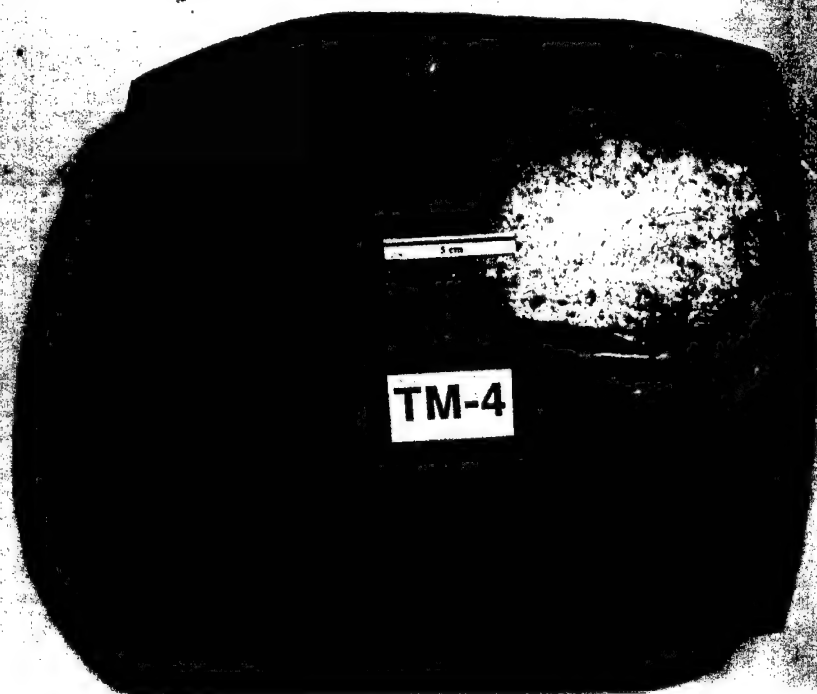Figure 5.2.3:   Panel TM-3 contained cap flaws.

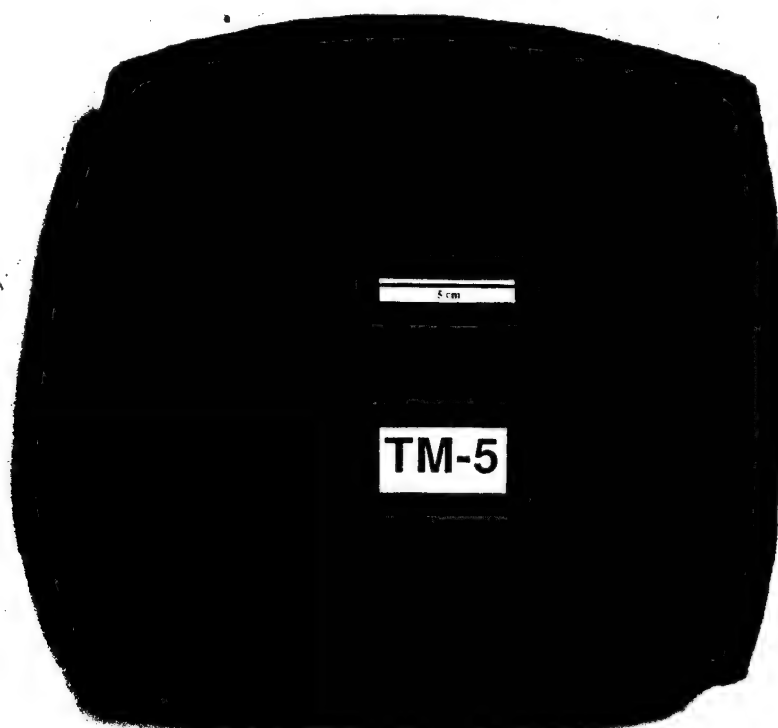Figure 5.2.4:   Panel TM-4 contained root flaws.
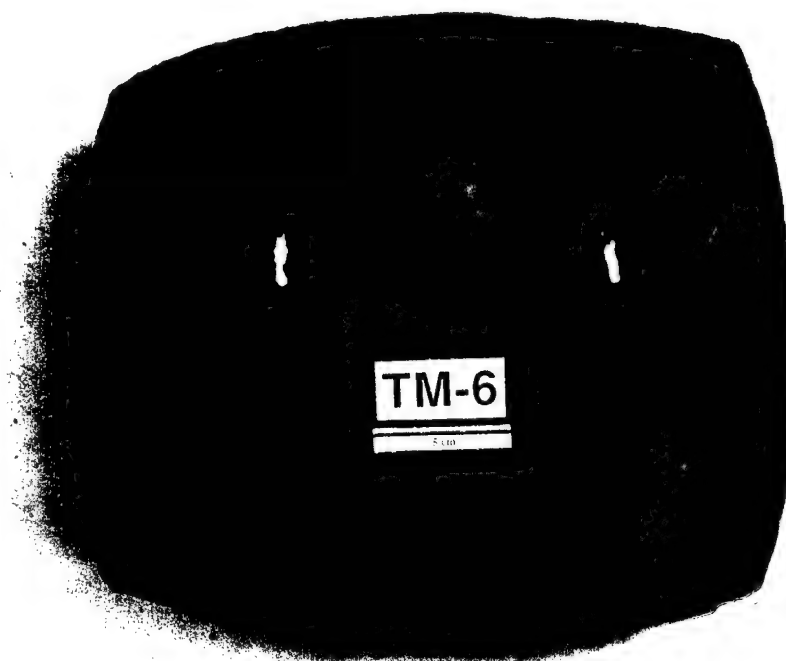
Figure 5.2.5:   Panel TM-5 contained cap flaws.

Figure 5.2.6:   Panel TM-6 contained cap flaws. (yellow marks indicate the initial flaw
length determined by UT)

6.0 METALLOGRAPHY

The tested explosion bulge panels were broken open at the weld when immersed in liquid nitrogen employing a three point bending arrangement.[6] The objective was to expose both the initial flaws resulting from a lack of fusion, and those that propagated as a result of the explosion bulge test. This exposure was required to display the surfaces and to perform metallography and necessary fractography to attempt determination of the location of the initial flaw, final flaw and its fracture mode. These results also provided information on the propagation behavior of the initial flaws under shock loading.

The test panels were first reduced in size by removing the excess length of weld so that the total remaining weld length extended 13 mm beyond the extremes of the flaw emerging at the convex surface or the UT based initial flaw length, whichever was greater. The entire remaining weld length was then immersed in liquid nitrogen and subjected to a three point bend with the convex surface taking the tensile load. This method of fracturing the test panels resulted in exposing both sides of the flaw for most of its entire length. One side was selected for display and the other was used for the extraction of specimens for scanning electron microscopy (SEM) and cross sectional metallography.

The mechanism of flaw propagation was identified as ductile as observed and by microvoids under the SEM.

6.1 Fracture Surface Inspection

After cleaning to remove surface rust, the fractures were examined visually. The length, location with respect to thickness, and mean depth of the initial flaws were measured on the exposed fracture surface. These measurements were compared with those made earlier using ultrasonic inspection and radiography.

Figure 6.1.1 indicates a typical fracture resulting from the presence of root flaws. The thinner arrows indicate the length of the initial flaw while the thicker arrows show the extent of the final flaw.

Figure 6.1.2 is typical of a panel containing cap flaws where explosion bulge testing only results in propagation of the flaws to the convex side. The initial flaw on the concave side is visible and it is clear that they did not propagate during testing. Compared to the through-thickness flaw propagation in panel TM-4, the cap defects display a relatively small extension during explosion bulge testing because they were subjected to fewer shots and thus less deformation. Further, the fracture exposed the initial flaw and propagation only for what appeared to be a portion of its entire length.

Table 6.1.1 indicates the lengths, approximate location in relation to the nearest surface, and the depths of the initial flaws as observed on the fracture surfaces. Figures 6.1.3(a) to 6.1.3(f) show the schematics of these results.

Table 6.1.1: Fracture surface inspection results of initial flaw size and location for the 6 plates.

Plate	Flaw Type	Length (mm)	Depth[@] (mm)	Location (mm)
TM-1	root	68 *	1.5-5.0	10
TM-2	cap, side 1	65 *	0.5-3.5	2.5
TM-2	cap, side 2	54 *		2.5
TM-3	cap, side 1	90 *	0.5-3.0	4
TM-3	cap, side 2	81 *		4
TM-4	root	117	1.5-5.0	10
TM-5	cap, side 1	91 *		2.7
TM-5	cap, side 2	59 *	0.5-1.5	2
TM-6	cap, side 1	76 *		2.3
TM-6	cap, side2	106 *	1.0-4.0	2.3

* not continuous
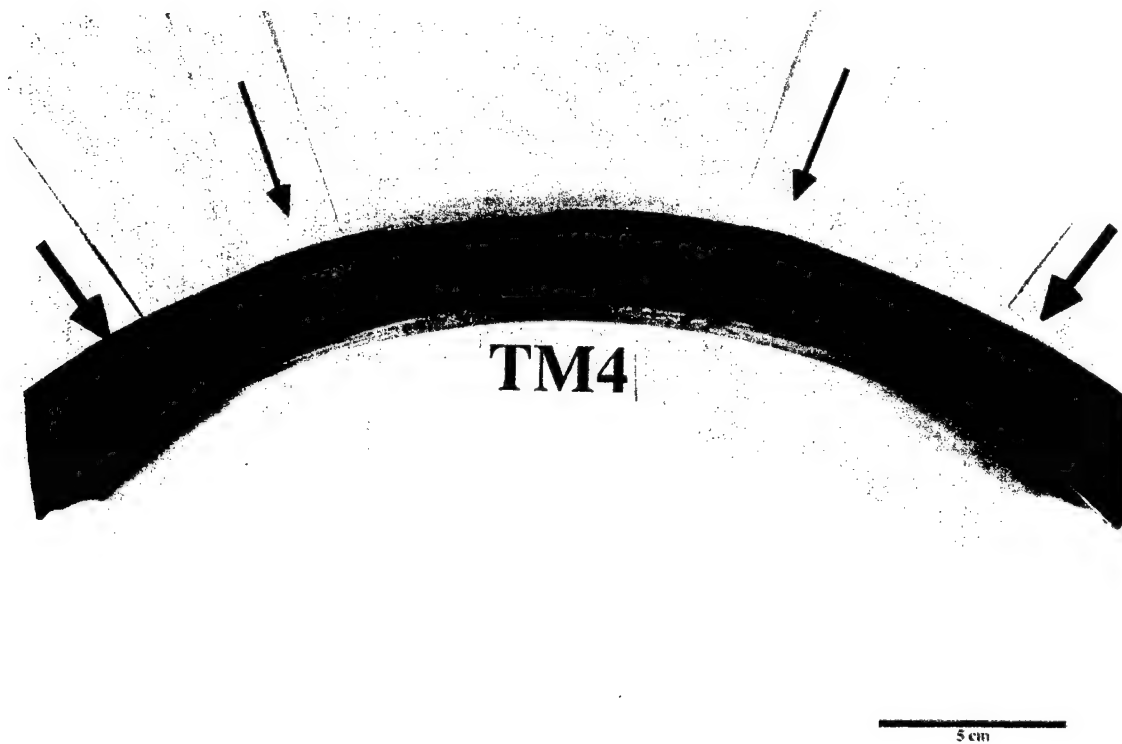[@] depth range was measured in the flaw close to the convex surface only

Figure 6.1.1: Fracture surface of panel TM-4 containing root flaws. The arrows indicate extremes of initial and final flaws.
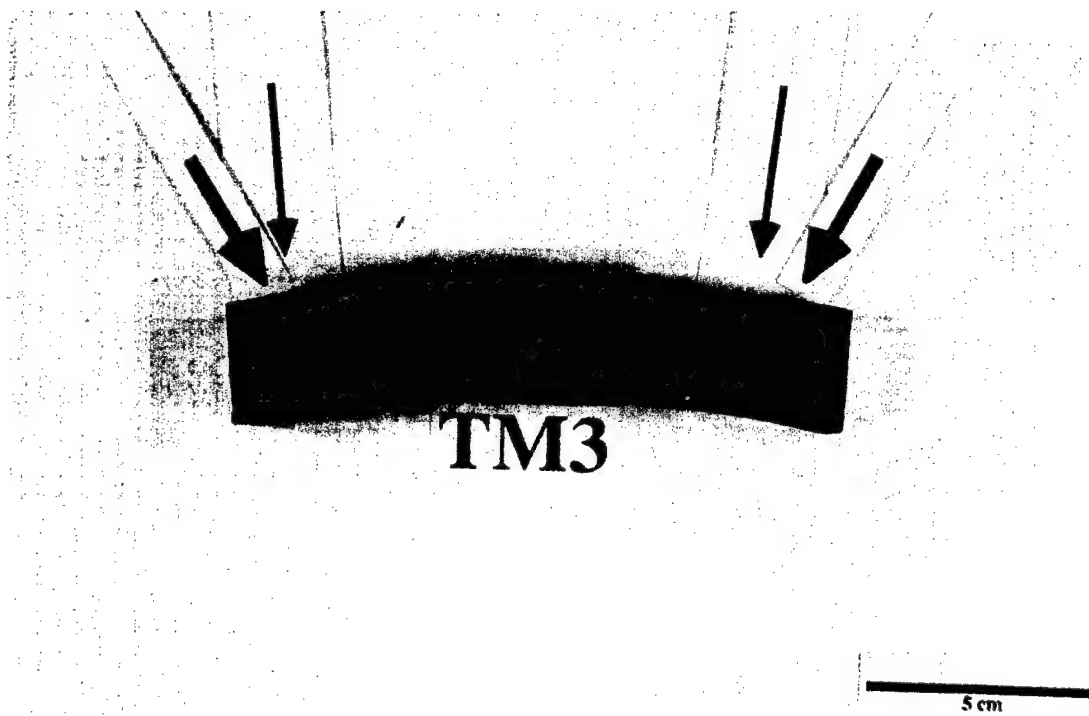

Figure 6.1.2: Fracture surface of panel TM-3 containing cap flaws. The arrows indicate extremes of initial and final flaws on the convex side.
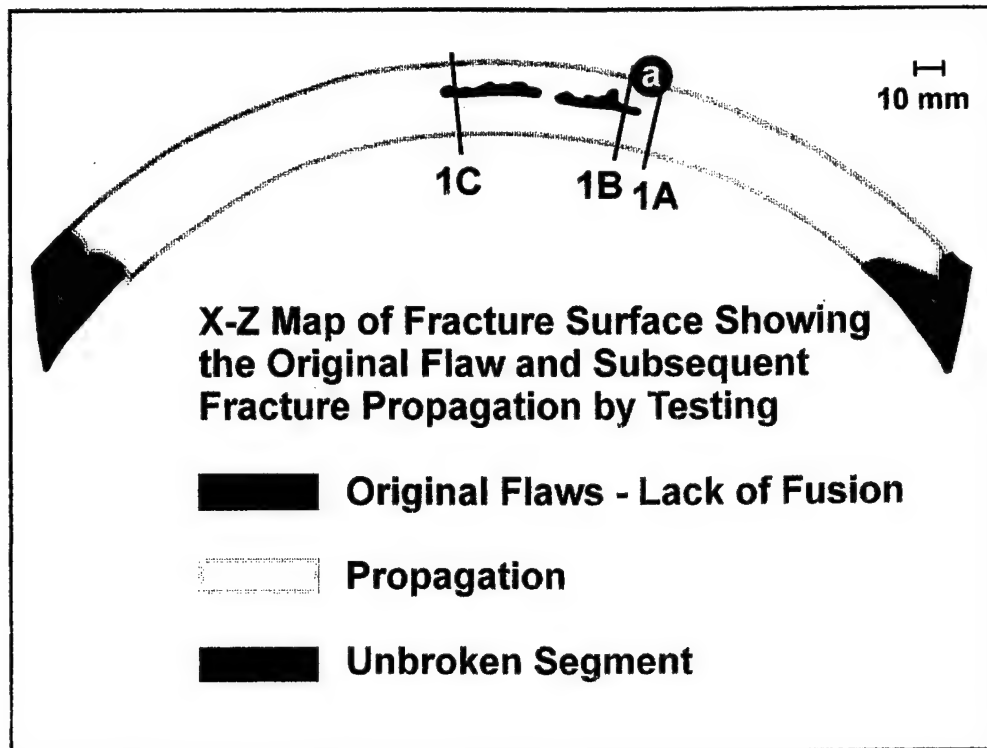
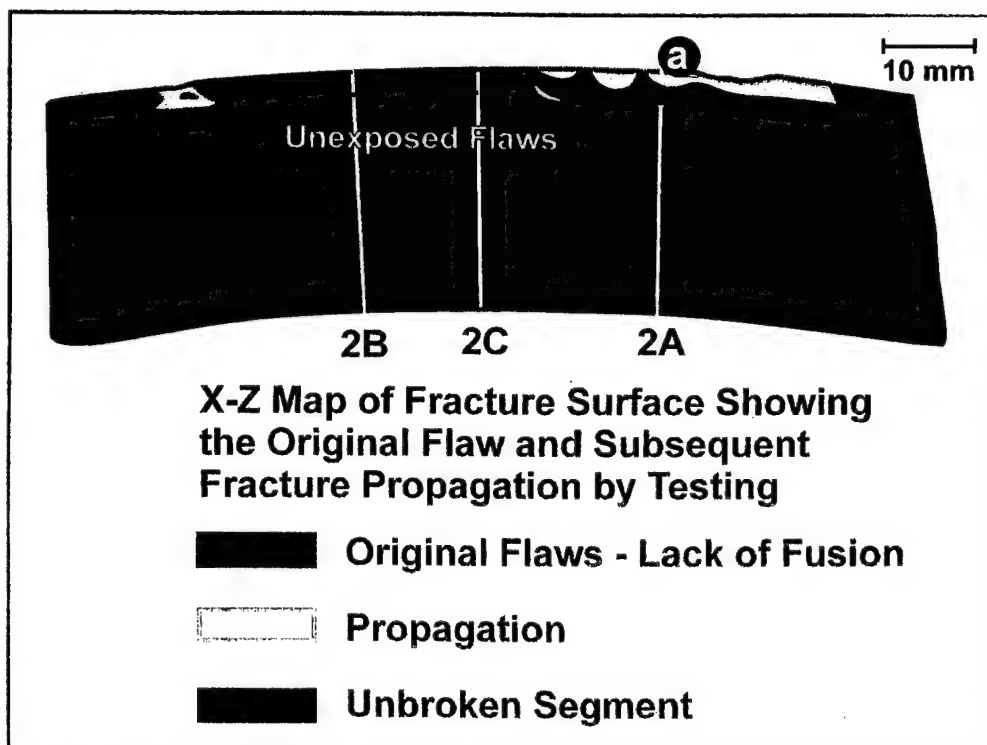Figure 6.1.3(a): X-Z map for panel TM-1
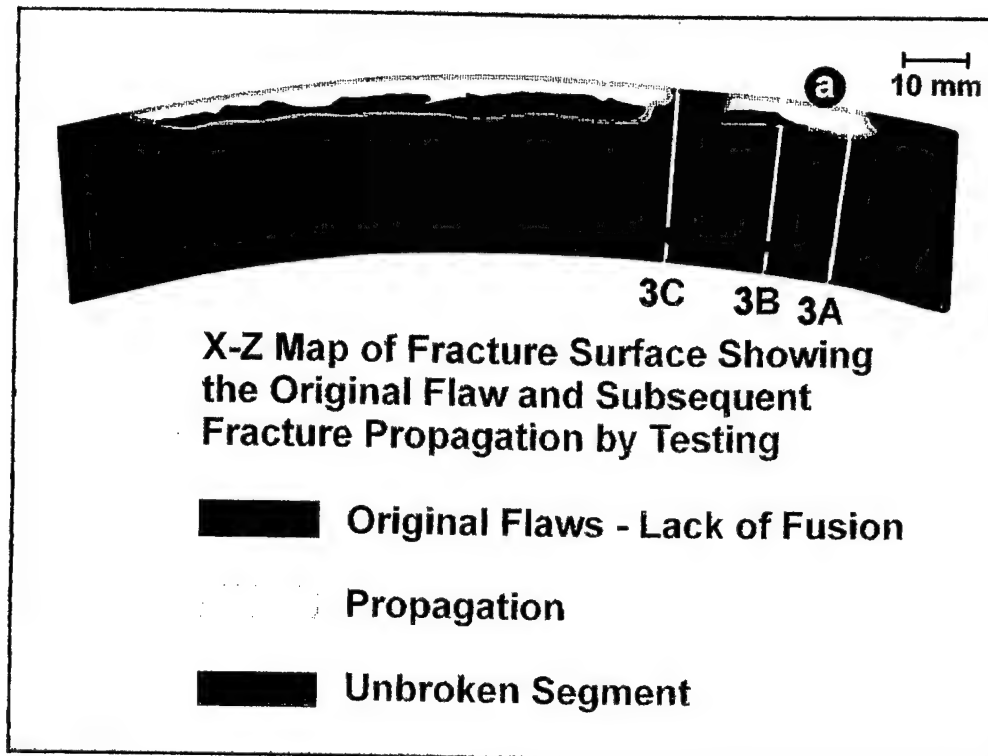

Figure 6.1.3(b): X-Z map for panel TM-2
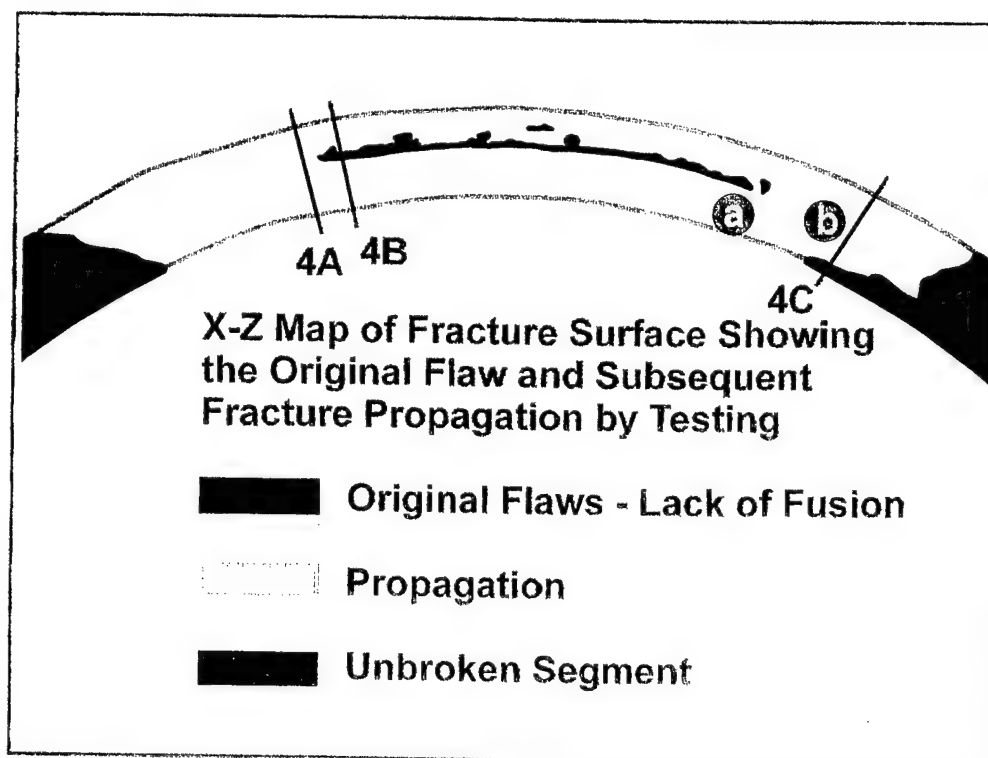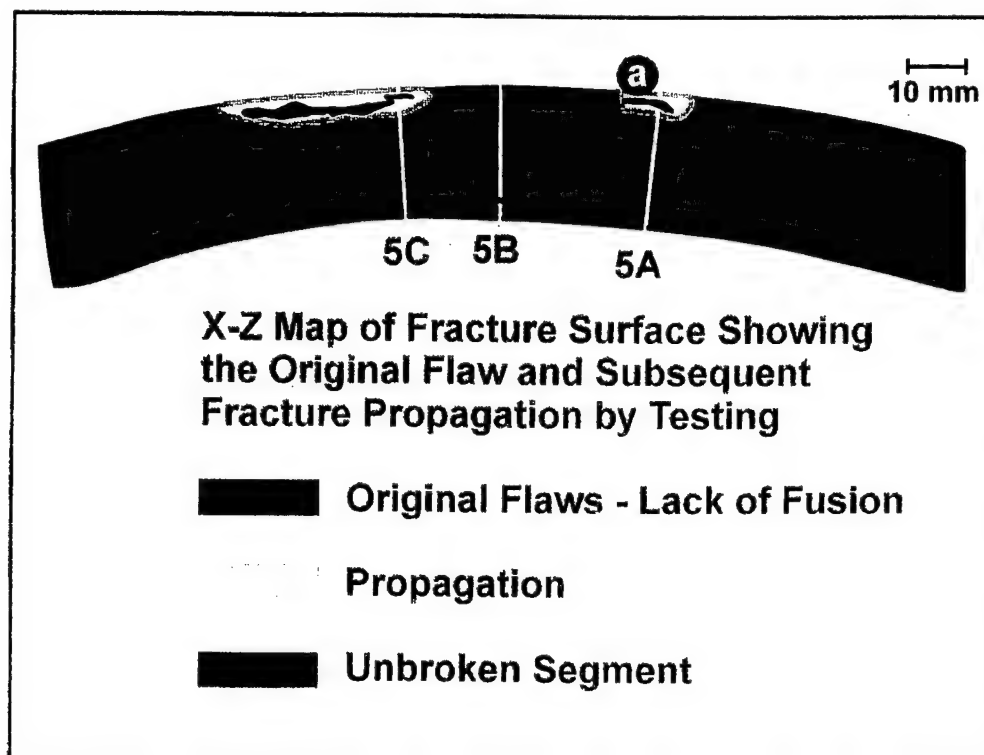
Figure 6.1.3(c): X-Z map for panel TM-3
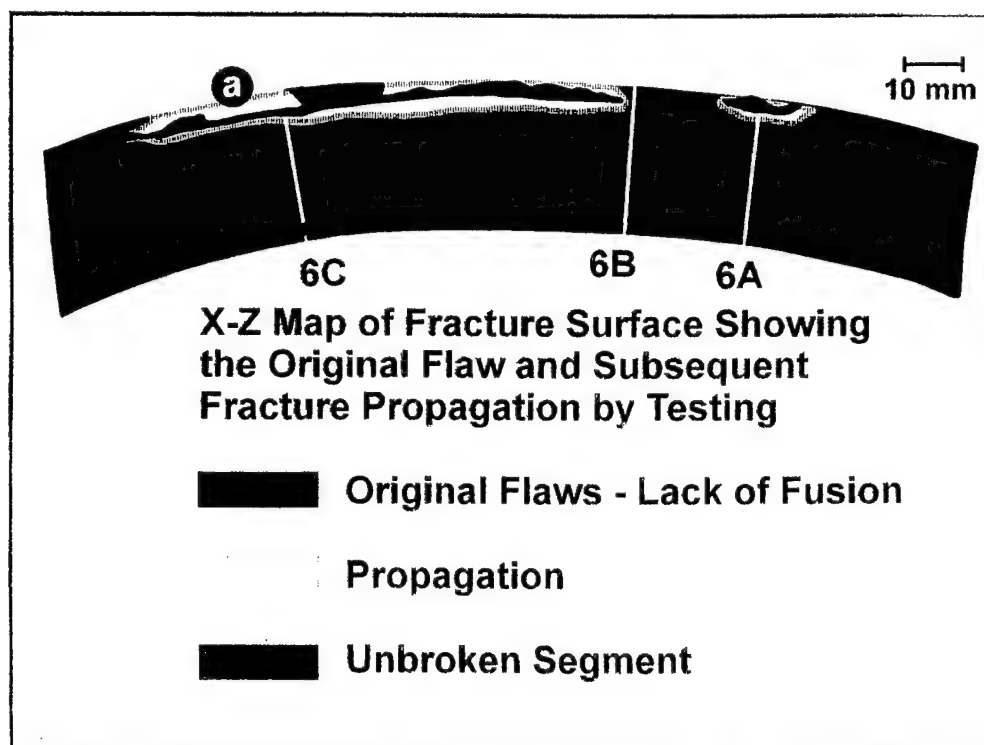

Figure 6.1.3(d): X-Z map for panel TM-4

5C **5B** **5A**

**X-Z Map of Fracture Surface Showing
the Original Flaw and Subsequent
Fracture Propagation by Testing**

Original Flaws - Lack of Fusion

Propagation

Unbroken Segment

Figure 6.1.3(e): X-Z map for panel TM-5

6C **6B** **6A**

**X-Z Map of Fracture Surface Showing
the Original Flaw and Subsequent
Fracture Propagation by Testing**

Original Flaws - Lack of Fusion

Propagation

Unbroken Segment

Figure 6.1.3(f): X-Z map for panel TM-6

6.2 Scanning Electron Microscopy

After visual examination selected areas of the fracture surface were selected for examination under the stereoscope at magnifications of 10 to 30X to determine the location and boundaries of the initial and final flaw sizes. These examinations confirmed that the initial flaw surface was relatively featureless (see Figure 6.2.1) while propagation of the flaw resulting from the explosion bulge testing occurred by the ductile fracture mechanism, as indicated by microvoids (Figure 6.2.2).

6.3 Cross-Sectional Metallography

At select locations, through thickness cross-sections were extracted to confirm initial flaw locations and determine flaw propagation with respect to the weld microstructure. The observations made on these cross sections indicate that the initial flaws delineated in the fracture face with a featureless appearance were indeed at the weld root for specimens TM-1 and TM-4. The propagation that occurred outside this region was in the weld metal, in the HAZ or in the base metal depending on location. In the region of flaw propagation, the microstructure adjacent to the fracture indicated some plastic deformation on the cross sectional metallographs. From the test specimens, through thickness cross sections were extracted from several locations: some from regions containing the initial flaw and some from outside these regions.

The observations made on the cross sections of a typical weld with root flaws, plate TM-4, indicate that the initial flaw delineated in the fracture face with a featureless appearance, is indeed at the weld root (Figure 6.3.1) and propagation of the flaw through the thickness occurred in the heat affected zone (HAZ) or in the base metal. Figure 6.3.2 is a cross section outside the initial flaw but is located in a region where propagation occurred through the thickness. This figure shows that the propagation is in the weld metal. Thus, in general, propagation of the flaw took place in the weld metal, in the HAZ, or in the base metal, depending on location. Figure 6.3.3 presents a micrograph giving indications of plastic deformation of the microstructure in a region of flaw propagation.
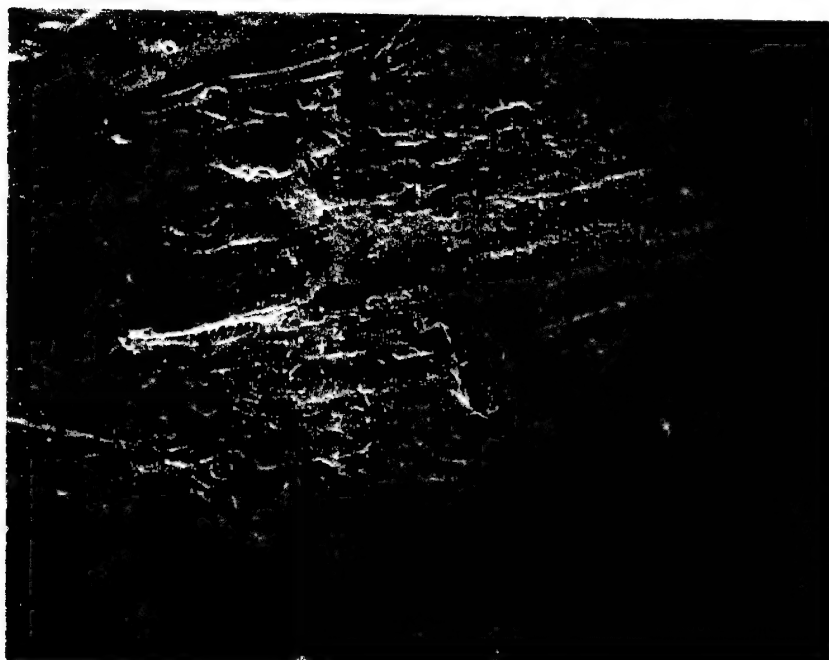
Figure 6.2.1: SEM view of the typical appearance of the initial flaw area (TM-4).

Figure 6.2.2: SEM fractograph of typical explosively torn area displaying propagation by microvoids.

The cross-sectional metallographs of panels with cap flaws indicate that the initial flaws delineated in the fracture face with a featureless appearance were indeed in the cap passes of the weld and that the propagation occurred in the weld metal on both sides of the initial flaw in the radial direction (see Figure 6.3.4). These fractures did not expose a continuous initial flaw on the fracture surfaces (see Table 6.6.1). Cross-sections were therefore extracted in all of these fractures at positions that do not show the propagation of the flaw. Using these an attempt was made to establish if the flaw was indeed continuous on the convex side of the panel. They showed that these defects are at different interpass locations. Therefore, compared to root defects which are associated with the single root pass, the cap defects are associated with one or more of the cap passes.

Two cross-sections were also taken in panel TM-2 from the fracture surface portion that did not expose the flaw on the fracture surface but within the two exposed flaws. These cross-sections displayed cap flaws that did not propagate but were aligned with the flaw that propagated to the convex surface. Compared to the other three panels that indicated the cap flaws to be non-continuous, TM-2 on the other hand, had a continuing cap flaw on the convex side that was not exposed to the fracture surface at least at the two locations where macrographs were prepared (Figure 6.3.5). These flaws are presented as a broken line at these locations in the X-Z map.
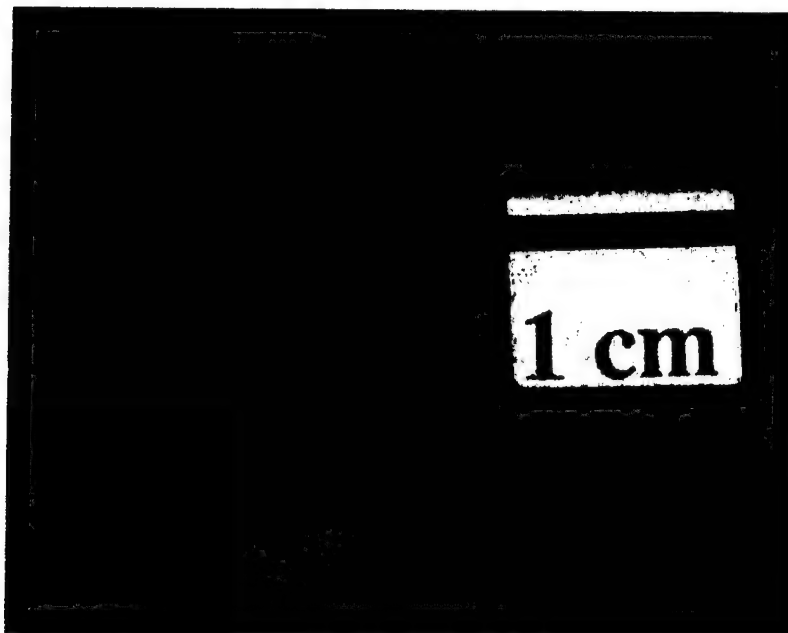
Figure 6.3.1: Macrograph of a cross-section (from TM-4) located at an extreme end of the initial flaw indicating that the flaw is associated with the weld root pass made from side 2. (Top side is the convex surface).
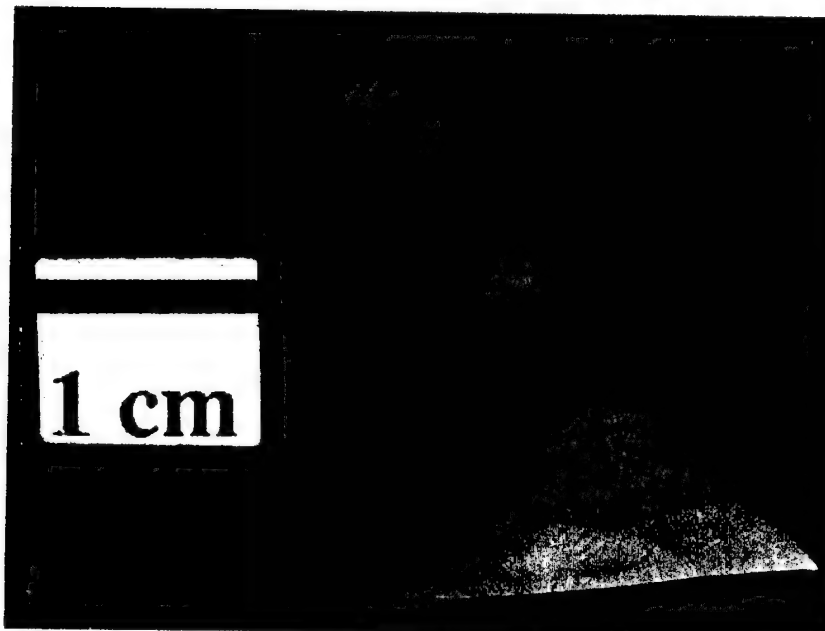

Figure 6.3.2: Cross section (from TM-4) located outside the initial flaw indicating an example where propagation occurred in the weld metal.
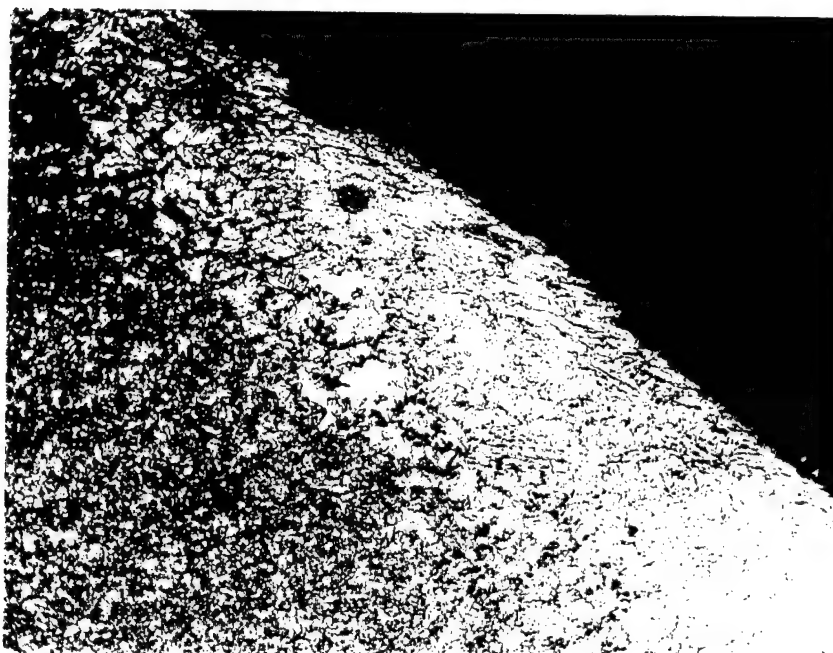
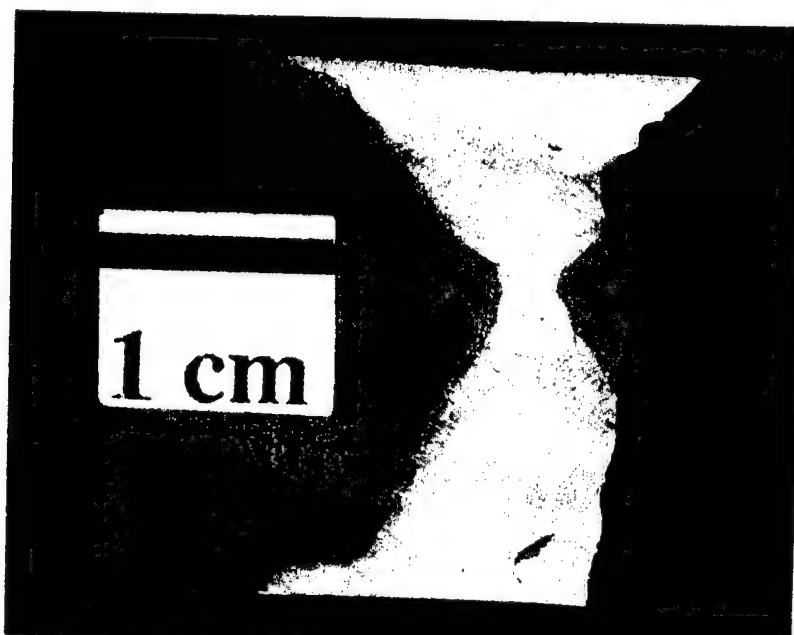Figure 6.3.3: Micrograph from a cross-section (from TM-4) indicating plastic deformation in the flaw propagation region. (200X)
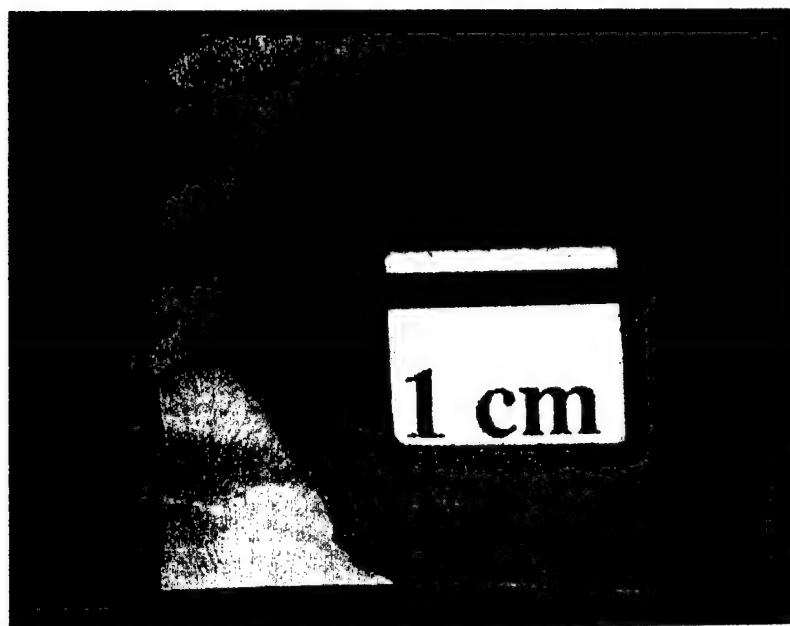

Figure 6.3.4: Macrograph of cross-section (from TM-5) at location that exposes the initial flaw at the convex side of the fracture face. (Top side is the convex surface).
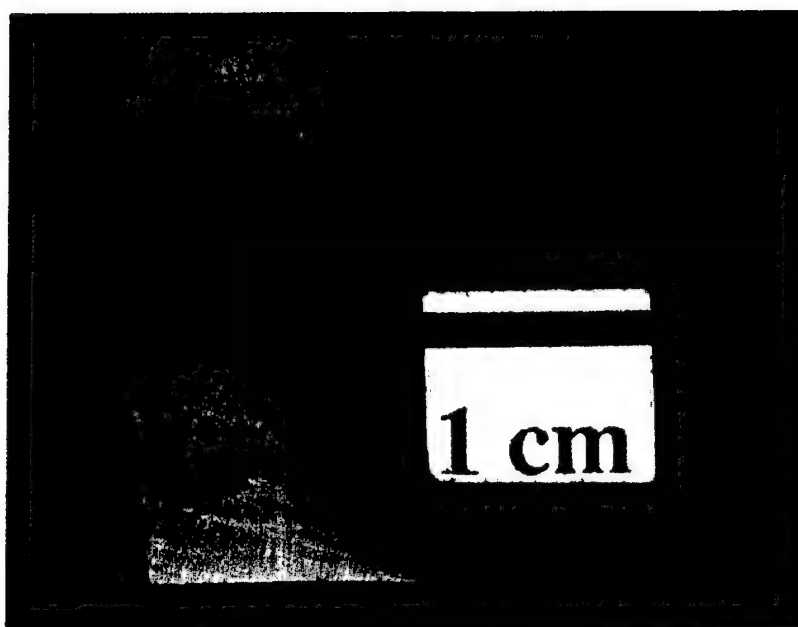
(a)

(b)

Figure 6.3.5: Macrographs of cross-sections (from TM-2); one from a location that exposes the initial flaw at the convex side of the fracture face (a), and the other from a location that does not expose the initial flaw, (b). (Top side is the convex surface).

6.4 Metallography Summary

The flaws seemed to generally propagate radially outwards and simultaneously along the complete perimeter. A unique initiation site could not be established. The initial flaw area was identified as a featureless surface whereas the extension of this flaw displayed a coarser fracture surface.

The welded explosion bulge test panels performed in one of two different ways depending on the flaw location. The two welds made with controlled root flaws resulted in propagation of these initial flaws through the thickness of the plate as well as along the weld length for a significant distance. The remaining four test panels had cap flaws, and in this case the propagation occurred mostly on the convex side. In contrast, the length of the final propagated flaw was only slightly extended for cap flaws (because of the single shot), and the propagation took place primarily towards the outer convex surface. The propagation of the initial flaw in all six panels was in the ductile mode as indicated by microvoids observed by SEM fractography.

Cross-sectional metallography confirmed that the initial flaws, especially the root flaws, were located in the controlled regions. In the case of the cap flaws, the indication was that in some regions, controlled flaws were not continuous but occupied different interpass locations along the width of the capping passes. Therefore, compared to root defects which are associated with the single root pass, the cap defects are associated with one or more of the cap passes. This appeared to be one of the primary reasons for the exposure of intermittent flaws in the fractures of the panels with cap defects. Complete metallographic results may be found in reference 6.

7.0 DISCUSSION

7.1 NDT/Metallography

The NDT results (Table 7.1.1.1) in comparison to the actual initial defects showed that manual ultrasonic, enhanced radiographic and computer-aided ultrasonic correlated well. The computer results gave depth indications which also correlated well. The

enhanced radiographic results (plus and minus 20° analysed together) perhaps correlated best with the actual fractographic results.

Table 7.1.1: Comparison of radiographic, manual ultrasonic and computer-aided ultrasonic initial defect lengths.

Plate		Radiography	Manual Ultrasonic	Computer-Aided Ultrasonic	Fractography
TM-1		67 mm	51 mm	38 mm	68 mm
TM-2	side 1	69 mm	51 mm	51 mm	65 mm
TM-2	side 2			51 mm	54 mm
TM-3	side 1	93 mm	51 mm	64 mm	90 mm
TM-3	side 2			64 mm	81 mm
TM-4		112 mm	102 mm	114 mm	117 mm
TM-5	side 1	70 mm	102 mm	102 mm	91 mm
TM-5	side 2			127 mm	59 mm
TM-6	side 1	84 mm	102 mm	127 mm	76 mm
TM-6	side 2			127 mm	106 mm

7.2 Explosion Bulge

The cap defect plates showed less deformation because the tests were halted after one shot when the defect broke to the surface (average strain of 12.3%). The root defects were slower to reach the surface (2 shots with an average total strain of 17.0%).

7.3 New Criteria

There is an overriding observation here that may have escaped many people in the past. The propagation of defects may not be a function of the defect's size and location so much as the base toughness and ductility of the adjacent weld metal and steel.

This reasons that it is the base properties of the steel and weld that are critical to the amount of propagation (not simply the defect size and location). We may need to rethink condemnation based on these observations.

It is quite possible that the focus should be on nondestructive examination of weldment properties in determining acceptance as opposed to just defect sizing. In any

event, the lack of exaggeration of tearing due to the various defects suggests that the defect size and location acceptance criteria can be greatly relaxed.

8.0 CONCLUSIONS

1. Defect size and location has less effect on propagation of defects than previously thought.

2. Base properties of welds and steel (i.e. toughness) are clearly a more significant factor than defect size and location in defining propagation (i.e. tearing versus brittle fracture).

3. The focus should switch from mapping defects to nondestructive determination of toughness in future weld acceptance criteria.

9.0 REFERENCES

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3. Matthews, J.R., Hay, D.R. and Chan, R.W.Y., "Computer-Aided Ultrasonic Inspection of Submarine Pressure Hulls", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 9, Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1990.

4. Porter, J.F., Morehouse, D.O. "Review of DREA Explosion Bulge Testing". 2nd CF/CRAD Meeting on The Fabrication and Inspection of Submarine Pressure Hulls, 26-28 May, 1987.

5. Mil-STD-2149 (SH), "Standard Procedures for Explosion Testing Ferrous and Non-Ferrous Metallic Materials and Weldments", November 1983.

6. Pussegoda, L.N., and Malik, L., "Metallurgical Evaluation of Defects in Explosively Loaded Plates", Fleet Technology Ltd., DREA Contractor Report CR/95/501, January 1996.
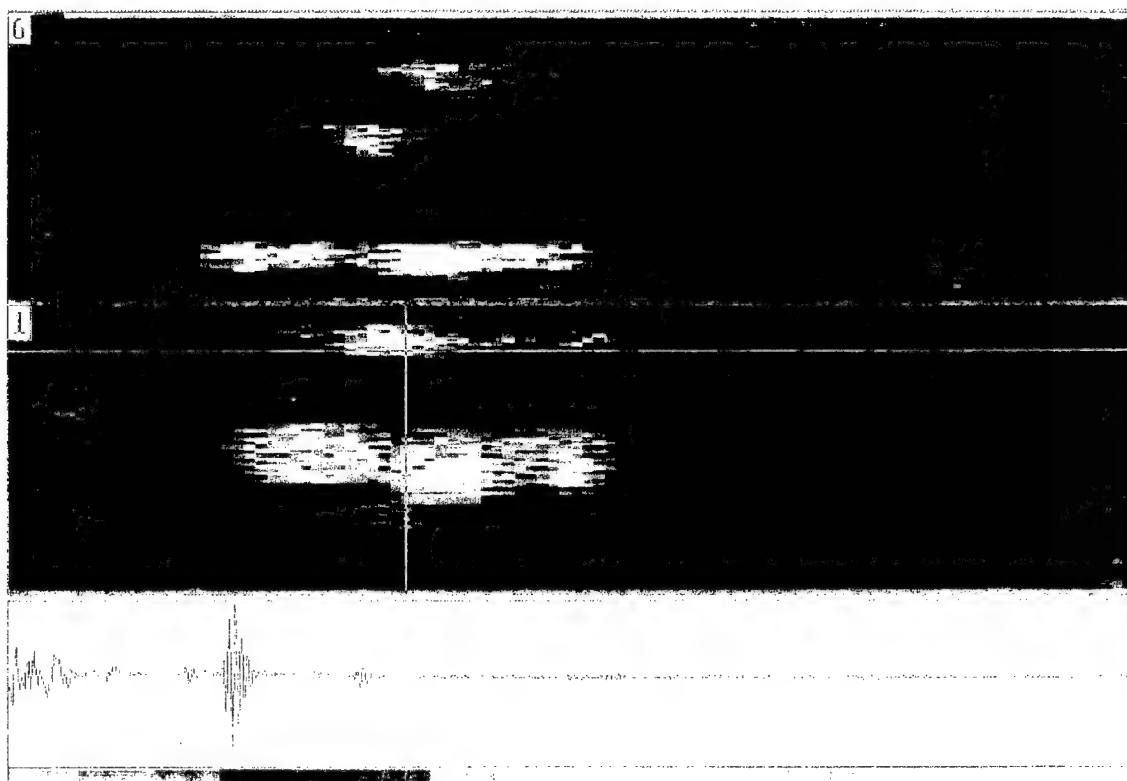
ANNEX A

APHIUS Printouts

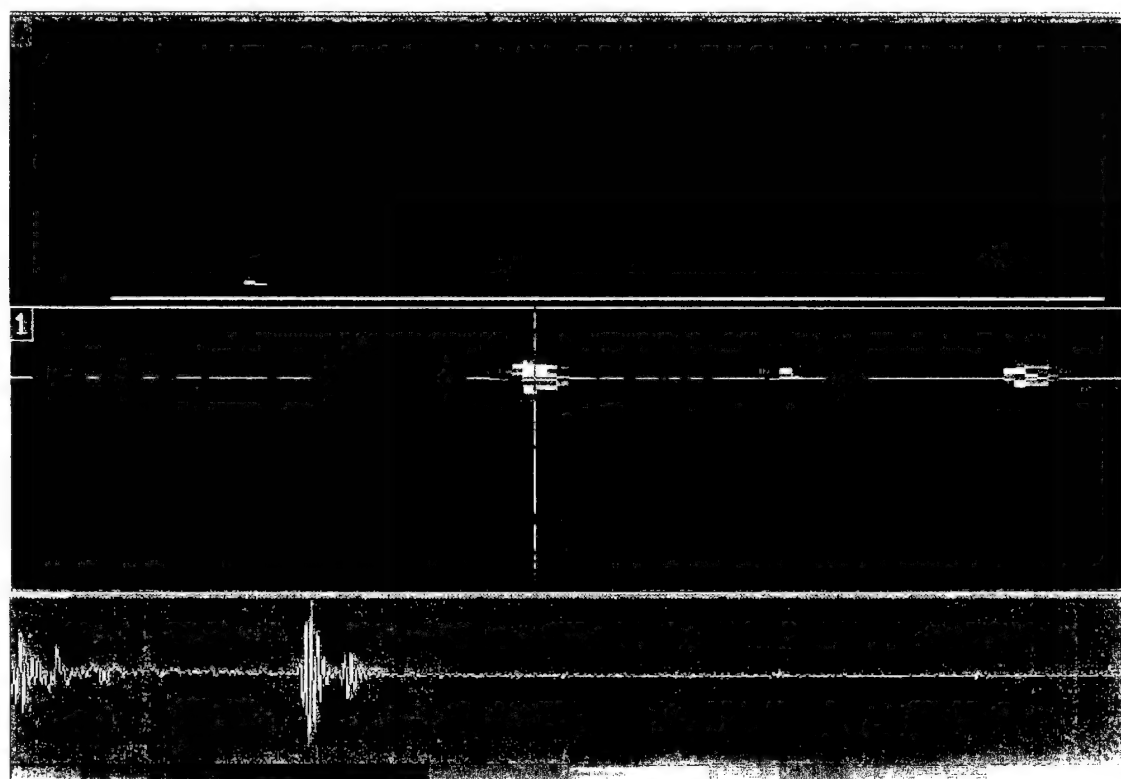Figure A-1: Computer-aided ultrasonic scan for plate TM-1.

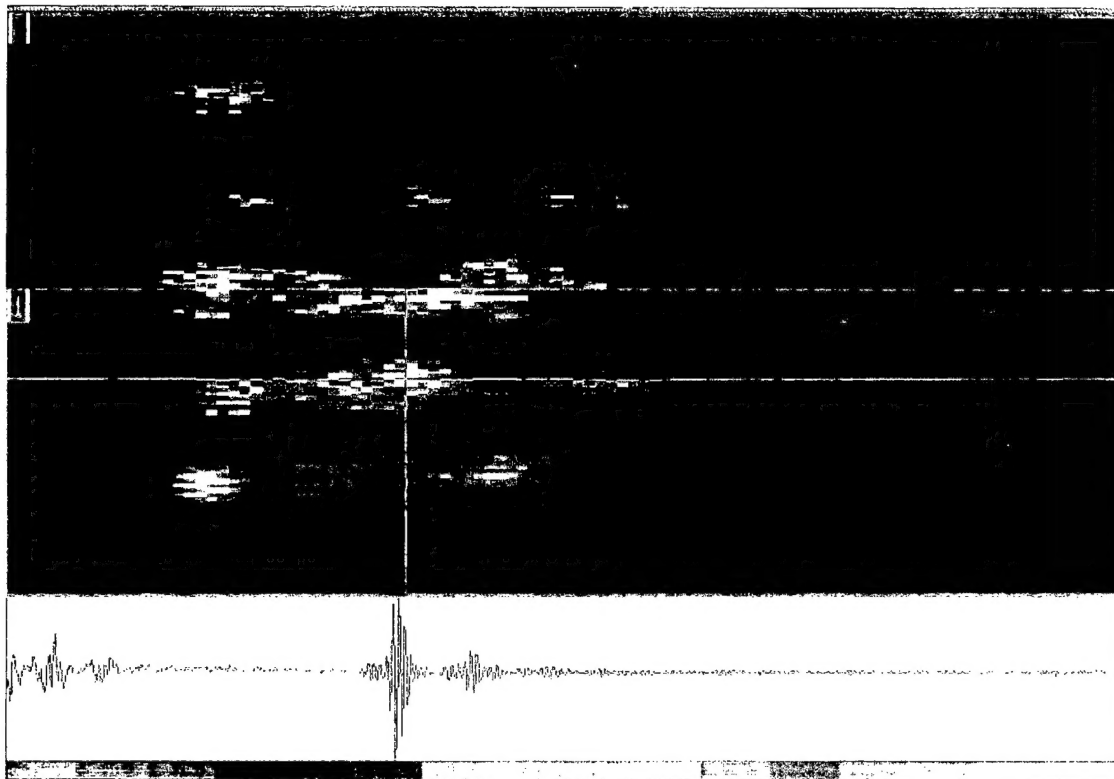Figure A-2: Computer-aided ultrasonic scan for plate TM-2.

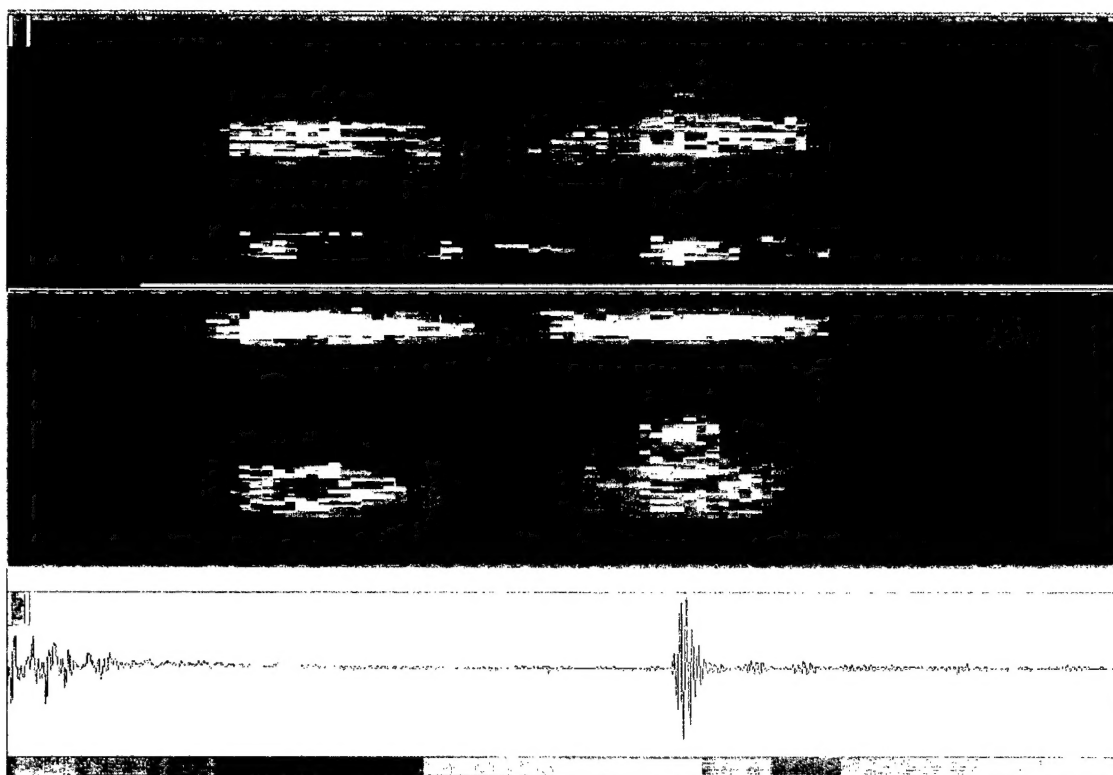Figure A-3: Computer-aided ultrasonic scan for plate TM-3.

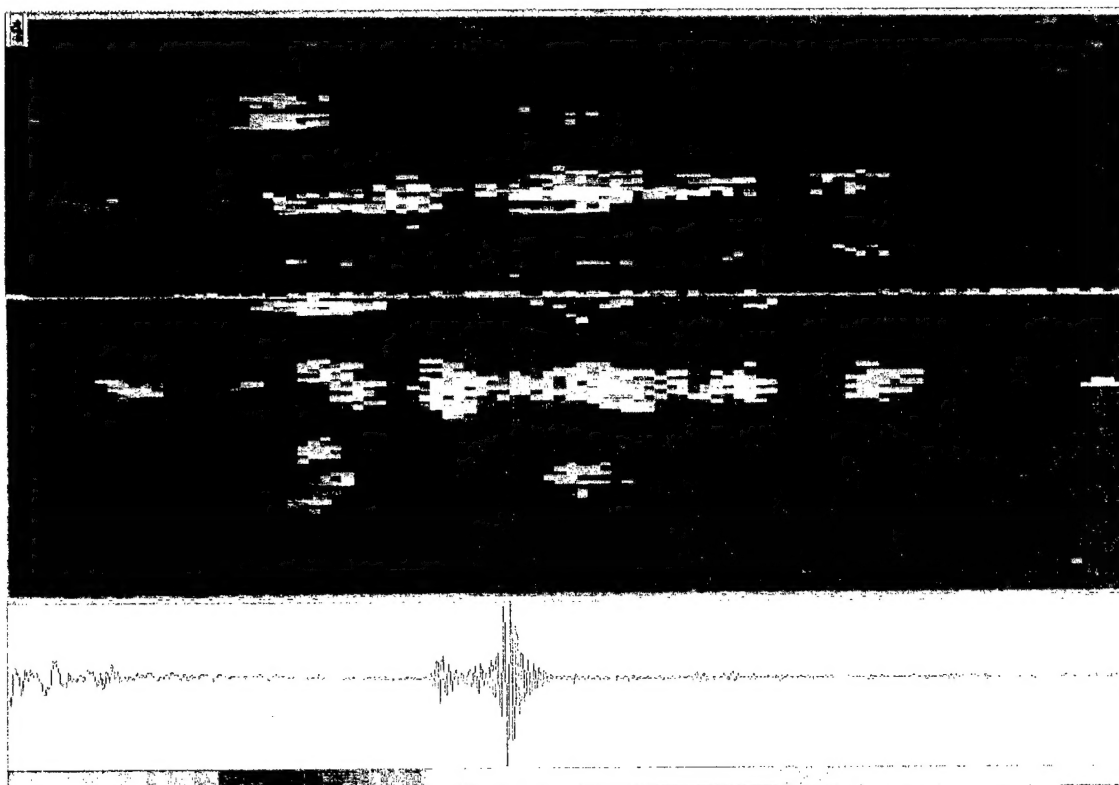Figure A-4: Computer-aided ultrasonic scan for plate TM-4.

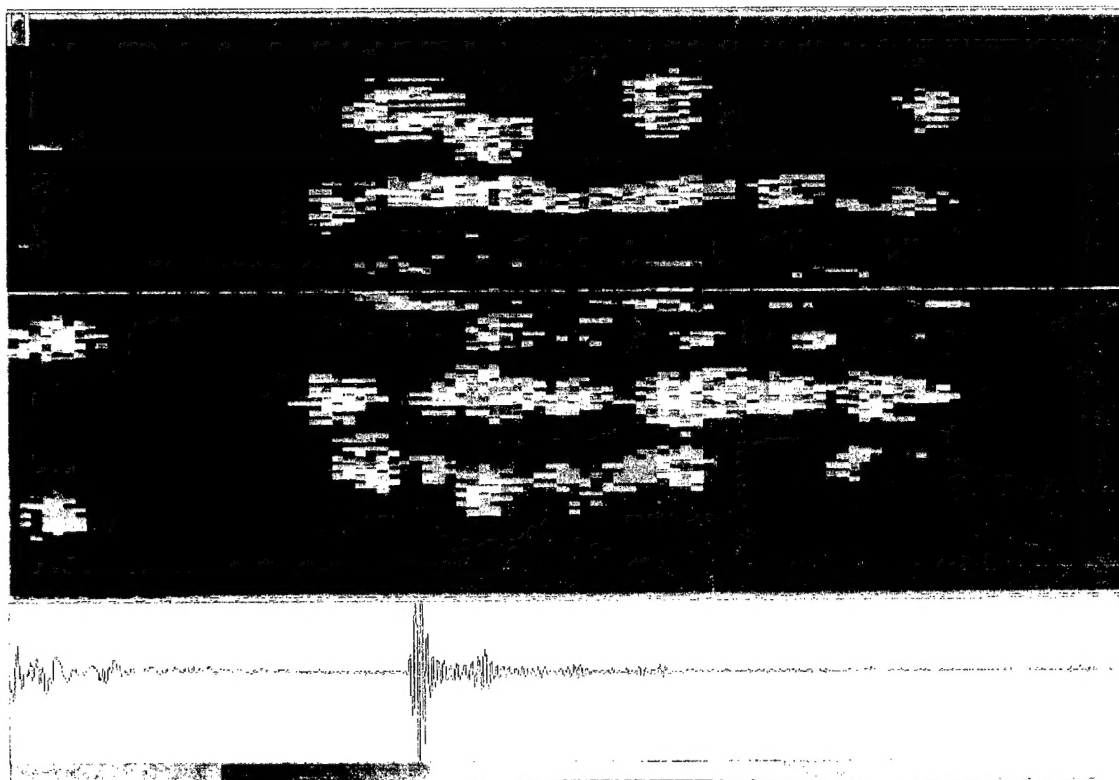Figure A-5: Computer-aided ultrasonic scan for plate TM-5.

Figure A-6: Computer-aided ultrasonic scan for plate TM-6.

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The British standards for submarine pressure hulls indicates that the presence of any lack of fusion defects in the weld is cause for rejection. However, depending upon the size and location of the defect, certain amounts of lack of fusion may be acceptable.

Six explosion bulge test panels were welded to have lack of fusion flaws; two panels had root flaws and the other four had cap flaws. Explosion bulge tests were performed to determine if the welds could resist crack propagation beyond the limits of the bulge apex.

Prior to testing, the welds were examined with manual ultrasonics and computer aided ultrasonics. They were also radiographed at plus and minus 20 degrees to normal (standard radiography would be shot at normal). The NDT was conducted to relate performance back to NDT (as opposed to just defect size and location).

Following explosion testing, the welds were sectioned and opened to determine the true defect extent.

Defect size and location was found to be less of a determining factor in the quality of the weld than the base properties of the weld and steel. It was found that condemnation criteria should be based on these base properties as well as on the size and location of defects.

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